■ Scientific Justification

Introduction

The acceleration of the universes expansion is one of the more captivating "key scientific questions of our day" identified by the NRC Committee on the Physics of the Universe (Tur02). In the few years since the acceleration was first seen in the Type Ia supernova (SN Ia) Hubble diagram (Per99, Rei98), the evidence has grown even stronger: complementary CMB measurements have indicated that the Universe has zero curvature (Xxx01), making the SN Ia result more determinative, and – in combination with the SNe – pointing to a $[\Omega_M \approx 0.3, \Omega_\Lambda \approx 0.7]$ cosmology. This is also consistent with other astronomical mass density measurements (Bah01,Tur01).

The SN Hubble diagram remains the only direct approach currently in use to study acceleration, and there is ongoing close study of the details of all known relevant sources of systematic uncertainty, but none show any biases at a level that might affect the basic acceleration results. These include: any changes with z in host-galaxy extinction by ordinary dust (Per99,Rei98,Sul02), any "gray" dust extinction undetectable by color (Pra03), gravitational-lensing (de)amplification of SN magnitudes (Per99,???), discovery selection effects (Per99,Rei98??), K correction systematics (Nug02), and population drifts in the SN environment (Sul02??).

With these advances in hand, we are now ready to pursue the cause of the acceleration, the "dark energy," be it a simple "energy of the vacuum" (Einstein's cosmological constant, Λ) or a general dynamical scalar field (as is assumed responsible for inflation). Although extremely challenging, we can in fact address this scientific question in several, ordered steps: the first large projects will test the hypothesis that the expansion is *consistent with* Λ, which is characterized by a constant "equation of state" ratio $w \equiv p/\rho = -1$. Later projects will lead to the still more difficult goal of detecting changes in w indicative of scalar field models. (The satellite experiment, *SNAP* has been proposed for this work.) This proposal is aimed at the first key step, testing Λ. By adding strategic HST observations for a sample of SNe Ia from a new, ambitious multi-year ground-based SN project, it will be possible to dramatically improve the efficacy of these next-generation SN Hubble diagrams for testing Λ.

Proposed Measurement: NICMOS constrains systematics

Redshift optimization studies have shown that for the case of a constant equation of state, and assuming that systematic uncertainties can be sufficiently controlled, the easiest test of a constant Λ can be accomplished with a well-measured Hubble diagram around $z \sim 0.5$. Large ground-based dedicated projects have now begun with the goal of collecting from 200 (CTIO "Essence" project) to 500 (CFHT SuperNova Legacy Survey, "SNLS") SN Ia lightcurves. The photometric uncertainty for each of these SNe will contribute statistical errors that are significantly smaller than the current estimates (Phi99) of intrinsic peak magnitude dispersion, $\sigma_{\rm peak} \approx 0.15$ mag, even after correcting for extinction and for lightcurve timescale (e.g. stretch or Δm_{15}). Given over 200 SNe, the statistical error for the Λ test will be $\sqrt{N}$ smaller, i.e. a statistical uncertainty of less than 0.01 mag. Since the current systematic uncertainties are much larger than this (Per99, PeSc03) the measurements from these large projects will be entirely systematics limited.

These major ground-based efforts are therefore only meaningful if the dramatic improvement in statistical uncertainty is matched by corresponding improvement in systematic uncertainty. The

Essence and SNLS projects both use discovery and follow- up strategies, and target redshifts, such that there would be negligible systematics from Malmquist bias, gravitational lensing, K corrections, or gray dust (given the Pae03 limit on its density). However, there are not good constraints on the intrinsic $B-V$ color of SNe Ia or the value of the reddening ratio, $\frac{R_B \equiv A_B}{E(B-V)}$ at the levels necessary to remove the systematics arising from any small changes in their values out to $z \sim 0.5$. There are also important tests of intrinsic SN population drift that remain necessary. We here propose to constrain these systematics by observing a significant sub-sample of 30 of the $z \sim 0.5$ SNe with NICMOS F110M imaging at their lightcurve maximum.

The F110M-band measurements correspond to restframe I band at these redshifts. When used with the full ground-based lightcurves in B and V, this HST observation will thus make it possible to obtain an $I_{\rm max}$ SN Ia Hubble diagram at $z \sim 0.5$, which is dramatically less affected by extinction – or by the uncertainty in the intrinsic SN color and R_B values needed to correct this extinction. Quantitatively, the current uncertainty in intrinsic SN color (after calibration for lightcurve width) is $\sigma^0_{B-V} \approx 0.03$ mag (Phi99), so the systematic uncertainty due to changes in this color of order half this disperion is $dA_B = R_B\sigma^0_{B-V}/2 \approx 0.06$ mag if a restframe B band Hubble diagram is used, but only $dA_I = R_I\sigma^0_{B-V}/2 \approx 0.024$ mag for restframe I band. If the $B-I$ color is used rather than $B-V$ the systematic uncertainty in I band drops to half this value, $dA_I = R_I/2.4\sigma^0_{B-I}/2 \approx 0.01$ mag, even though the intrinsic $B-I$ color is somewhat more uncertain, $\sigma^0_{B-I} \approx 0.045$ mag (Phi99). This drop in systematic uncertainty by adding the NICMOS data is the factor of ∼4.5 needed to begin to match the statistical improvement from the two major ground-based projects. Figure 2 shows that this improvement in systematic uncertainty makes possible the measurement precision of a constant w that is targeted by these ground-based projects.

The sample size for this NICMOS study is chosen so that this level of systematics control can be tested by comparing restframe $B-I$ intrinsic SN Ia colors from high- redshift and low-redshift SN samples. With intrinsic sample dispersions of approximately 0.05 mag in the low-redshift sample, a comparable assumed dispersion in the high-redshift sample, and an additional dispersion of 0.07 mag at high-redshift due to the proposed NICMOS observation SNR, and, finally, after splitting the sample into 1/3 ellipticals/S0s and 2/3 later-type hosts, a sample of 30 is required. It is important to note that a new sample of low-redshift supernovae are also being observed with I band observations over their lightcurve peak during the same planned study period, with a dedicated instrument with dedicated 88" telescope time at Mauna Kea (Ald01).

Note that one might have considered testing the intrinsic color drift by comparing SN colors in spiral host galaxies with those in ellipticals; however, this color difference would be confused with any population drift out to $z = 0.5$ *within* these host- galaxy subsets. We therefore test for intrinsic color drift separately within each of these host-galaxy subsamples, and then separately test for intrinsic SN population drift, as follows.

Testing intrinsic SN population drift systematics

The possibility of a drift over $z = 0$ to 0.5 in the distribution of SN host galaxy environments remains as a source of systematic uncertainty that must be tested. Elliptical and S0 galaxies would be expected to follow a much different evolution history than later-type galaxies, so a important test can be made by separately studying the Hubble diagrams from the two host-galaxy-type subsamples. Using several years worth of our HST data, we have recently published the first implementation of this test (Sul02), which showed the same cosmological results for a Hubble plot of 12 E/S0 galaxies as for a Hubble plot of 45 late-type galaxies (see Figure 5). The two subsamples agree within their ± 0.1 uncertainties for Ω_M or Ω_Λ in a flat cosmology. With the current proposal's NICMOS observations it will be possible to double the sample size for this important test. Together with the accompanying larger low-redshift sample, this test can be bring the constraint on this source of systematic uncertainty down below the 0.06 level; more of these tests will be needed to reach the final statistical goal, but these can be done with host galaxy Snapshot observations in the following HST Cycle after the supernovae fade. [[[Is there some other way we should quantify the amount of improvement in this test that we get by doubling the sample size???]]]

Testing Major Improvements in Statistical Uncertainty

If we can achieve this crucial level of control on systematic uncertainty, there is also an opportunity to push the statistical uncertainty even lower using this same NICMOS dataset, and also using an additional measurement for a subset. First, the rest frame I band maximum for SNe Ia is not only more robust to extinction, but it is also more "standard" with respect to light-curve timescale. Its slope with respect to Δm_{15} is half as steep in I as in B band (Phi99). Although there is much less data available to test the "standardness" of I_{rmmax}, the dozen SNe available with I band lightcurves that include I maximum already indicate a dispersion of ~ 0.11 mag, *uncorrected* for either Δm_{15} or extinction (see Figure 3). The proposed NICMOS dataset will test this new approach – and may suggest that the next samples of SNe should all be done in restframe I band (note that the ground-based supernova programs are four-to-five-year efforts, so this efficient observing program can be applied for in future HST Cycles).

For a subset of 10 of the 30 SNe observed in this program with NIC1 F110M at lightcurve peak, we propose one additional measurement with the same filter 17 days later. This measurement takes advantage of a remarkable consistency seen in the SN Ia color-magnitude diagram during this phase of the lightcurve. As shown in Wan03 (and Figure 4), every single well-measured SNe Ia shows a tightly defined linear relationship between the intrinsic brightness and the color during this phase, allowing a brightness calibration based on color that has even lower dispersion than those based on lightcurve timescale (like "stretch," Δm_{15}, and MLCS). The relationship between B maximum and B-I color is $B_{\rm max} = a + \beta_{BI}(B - I)$, where the slope is measured to be narrowly distributed around $\beta_{BI} = XXX \pm YYY$ during the period around day 17. Together with the standard B band extinction relation, one can solve for an extinction-free calibrated magnitude....

Conclusion

The two new ground-based supernova projects that have begun are committing very large amounts of dedicated telescope time with wide-field instruments to the goal of testing the possibility that dark energy is Λ. If they are to succeed the ground-based work must be complemented by redder photometry measurements that are only available with HST. We here propose a highly efficient use of NICMOS to achieve this goal, by providing the crucial improvement in control of systematic uncertainties necessary to match the statistical uncertainty, and offering the possibility of a further factor of two in statistical weight of each supernova.

References

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Bahcall, N. A., *et al.* 2000, ApJ, 541, 2000
Nugent, P., A. Kim, S. Perlmutter, 2002, PASP, 114, 803.
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Perlmutter, S., *et al.* 1999, ApJ, 517, 565.
Phillips, M., *et al.* 1999, AJ, 118, 1766,
Riess, A. G., *et al.* 1998, AJ, 116, 1009.
Sullivan, M., *et al.* 2003, submitted to MNRAS. astro-ph/0211444
Turner, M.S., *et al.* 2002, Report of the "Turner Panel", National Academies Press
Wang, L., *et al.* 2003, in preparation.

Description of the Observations

Exposure Times
This proposal requests 900-second NIC1 F110M exposures near maximum light for 30 supernovae (two supernovae will be observed per orbit); For an SN Ia at the proposed redshift, $z \sim 0.5$, the NICMOS ETC calculates that this will yield a signal-to-noise ratio (SNR) of 28. After the supernova fades (typically a year later), a final 900-second NIC1 F110M image will be needed to subtract off the host galaxy light from the image with supernova+galaxy; The NICMOS ETC calculates that the SNR of the subtraction of the two images will be 22. This is the minimum SNR required to provide a restframe $B - I$ color with uncertainty below 0.05 magnitudes, which keeps the extinction correction uncertainty below the intrinsic dispersion among SNe Ia.

The subsample of 10 supernovae to be studied around 17 restframe days past maximum will require an additional full orbit (2200- second[[[???]]]) observation; At $z \sim 0.5$, this will yield a SNR of 25 [[[???]]]. This subsample will require a full orbit (2200-second [[???]]) final host-galaxy image instead of the half orbit image.

The total requested orbit count would then be [TYPESET TABLE OR TABS] 30 SNe at 1/2 orbit each at max = 15 orbits
(OR drop this to 24 SNe ... = 12 orbit)
10 SNe at 1 orbit at day 17 = 10
20 SNe at 1/2 orbit final ref = 10
(OR drop this to 14 SNe ... = 7 orbits)
10 SNe at 1 orbit final ref = 10
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Total: 45 orbits
(OR drop this to total 39 orbits)
Note that 25 of these orbits would be scheduled this HST Cycle, and 20 the following Cycle.

Special Requirements

[ARE ANY NEEDED?]

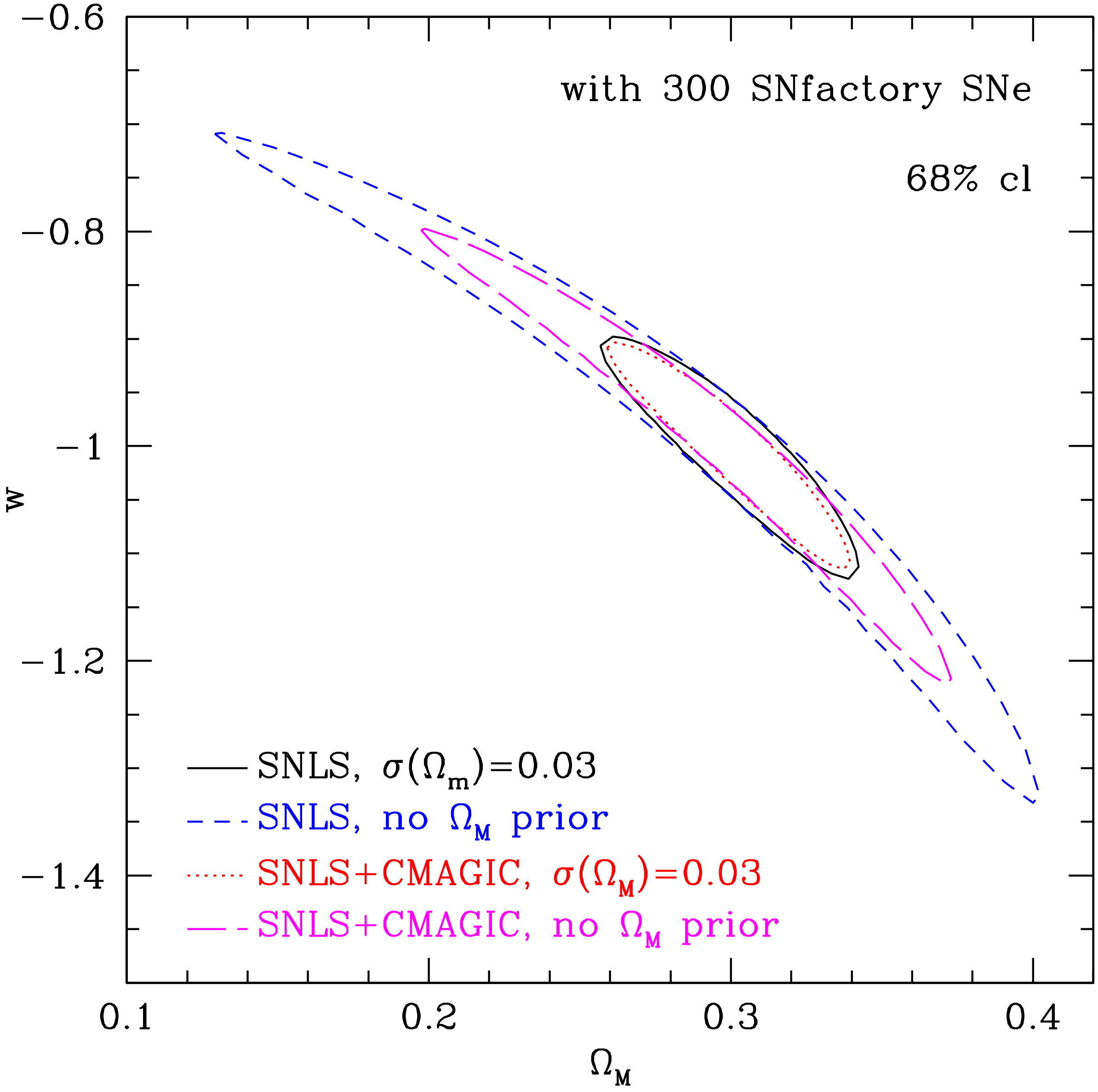

Figure 1: Caption fig 1

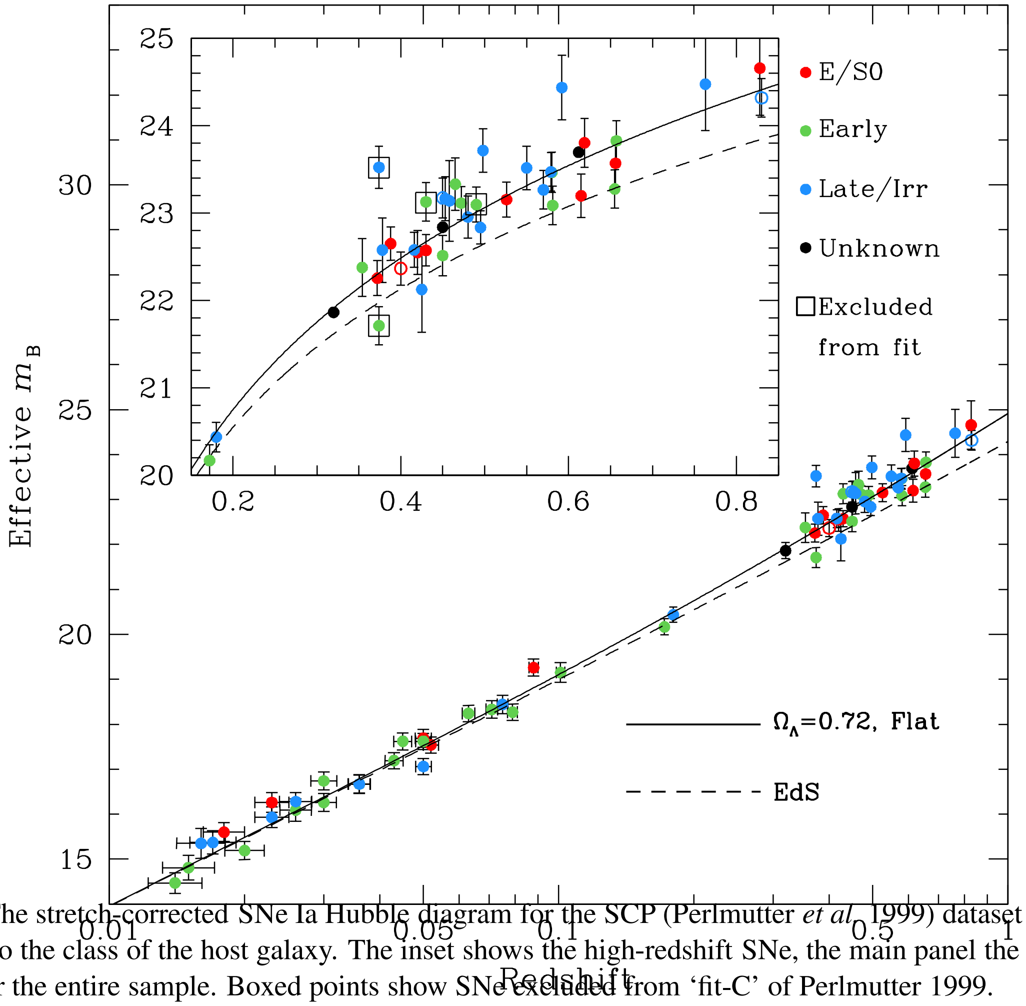

Figure 2: The stretch-corrected SNe Ia Hubble diagram for the SCP (Perlmutter *et al* 1999) dataset plotted according to the class of the host galaxy. The inset shows the high-redshift SNe, the main panel the Hubble diagram for the entire sample. Boxed points show SNe excluded from 'fit-C' of Perlmutter 1999. Supernovae in elliptical/S0 host galaxies show significantly less scatter than those in later types.

Coordinated Observations

Both the SNLS and Essence projects are discovering supernovae in a "rolling search" mode, in which the same fields are revisited every few nights (with observations in multiple filters) over several months. This means that every supernova can be discovered within a few days of explosion and then followed with photometry every few nights over the following few months. Most (or all) of the SNe that will be used for this current proposal will likely come from the SNLS set since most of the proposers are either affiliate or members of the SNLS team (in particular, Reynald Pain is a leader of that project), but the Essence data and discovery announcements are publicly available publicly as part of the NOAO Science Archive and we would be happy to follow those SNe as appropriate.

There are several advantages for this proposal from this mode of discovery and follow-up. First, there will be a continuous rate of supernova discoveries in the redshift range around z 0.5 - - approximately 40 per year from the SNLS search. This allows just a couple of orbits to be scheduled per week for this HST program (to follow 4 SNe per week at maximum light), providing more HST scheduling flexibility. These discoveries will all be in one of the few predetermined SNLS survey fields, which are small enough that the HST can be scheduled many weeks in advance to observe a target in the field and then the final exact coordinates given one week in advance of the observation. This observing mode (which we have used extensively for HST follow up of high-redshift SNe) avoids the wasted orbits of TOO observations.

The discoveries are triggered in restframe U, B, and V bands [[[IS THAT RIGHT?]]] several observer-weeks before the supernova reaches maximum light in restframe I band (which is just a couple of days before the B band maximum). The photometric redshift for the host galaxy is known from multiband photometry observed the previous year, allowing the selection of just the z 0.5 Type Ia SNe and a ±3 day prediction of the date of I band maximum. The "rolling search" and follow-up yields sufficiently high-signal-to-noise observations in restframe B and V band throughout the lightcurves of these SNe that the $B_{\max}$, $B - V$ color, date of maximum light (in B band, and hence in I band), and lightcurve timescale stretch (or Δm_{15}) will all be known to a precision that is better than needed for the known intrinsic dispersion of the methods.

As each z 0.5 SN Ia is identified, it will be slotted into the next available observing slot closest to its date of maximum light. The full-orbit observation at 17 restframe days ($\approx$ 25 observer days) past maximum for a previously observed supernovae will be used to fill an appropriate slot whenever its date is better suited than the next maximum light observation. [[[CHECK to make sure that this strategy roughly works out on average.]]]

Justify Duplications

None - these are all unique observations of transient events.

Previous Related HST Programs

GO-9705: Observations for this large (100-orbit) program started after servicing mission 3B in March 2002 and have mostly been completed, although some final reference images are still to be taken. Coordinated with three large search campaigns with the Subaru 8.2 m and also with smaller searches with the CTIO 4 m and CFHT 3.6 m, we used ACS/WFC and NICMOS/NIC2 photometry to obtain multi-epoch lightcurves of eight Type Ia SNe at high redshift $(0.9 < z < 1.3)$. For two of the highest redshift SNe, ACS grism spectra were taken. Analysis of this ACS data is in progress. With the refurbished NICMOS, we obtained final reference images of the host of SN1998eq, which we had previously studied in G0-8088, and these images will allow us to complete that analysis.

GO-8585: In GO 8585 we observed six Type Ia supernovae with HST using WFPC. The supernovae were discovered in ground based searches at the CTIO 4-m, CFHT and Subaru telescopes. We obtained both U- and B-band restframe photometry (using either F814W or F850LP depending on the redshift) for each supernova for a period of 2 months. Analysis of this data will be completed when the final reference images are available, scheduled for spring 2003.

GO-8313: The objective of this project, which has now been completed and submitted for publication, was to obtain snapshot unfiltered STIS images of distant galaxies of known redshift which have hosted supernovae (SNe) of Type Ia found by the SCP, 20 of which are used in the Hubble diagram of 42 type Ia SNe (Perlmutter *et al.* 1999). In Sullivan *et al.* (2002, submitted) we present these new results on the Hubble diagram of SNe Ia as a function of host galaxy morphology that demonstrates that host galaxy extinction is unlikely to systematically dim distant SN Ia in a manner that would produce a spurious cosmological constant. The internal extinction implied is small, even for late-type systems ($A_B < 0.3$), and the cosmological parameters derived from those SNe Ia hosted by (presumed) dust-free early-type galaxies are consistent with our previous determination of a non-zero Λ. The brightness scatter about the Hubble line for SNe Ia in these early-type hosts is also significantly smaller than for the SNe Ia in late-type galaxies. This result was based on HST STIS "snapshot" images and Keck spectroscopy of SNe spanning the range $0.3 < z < 0.8$.

GO-8346: We had the unique opportunity of following up SN200fr, which had been discovered *14 days prior* to maximum light in its restframe. Because this supernova at z=0.54 was discovered so early we were able to obtain excellent light curves from HST in F555W, F675W and F814W spanning the period from one week prior to maximum light to 6 weeks after Several spectra of the supernova were taken at VLT and Keck along with NIR photometry at VLT. To date, this is still the best observed high-redshift supernova.

DD-8088: WFPC2 and NICMOS (cycle 7) observations were obtained for SN1998eq at $z = 1.20$ (another record-breaking redshift for a spectroscopically confirmed Type Ia supernova; Aldering, *et al.*, 1998). The preliminary photometry (shown in Fig. 1) is consistent with the previous results for Ω_M, Ω_Λ. With the final NICMO image of the galaxy without the supernova recently obtained in cycle 11, this analysis can now be completed.

GO-7850 and balance of **GO-7336** and **DD-7590**: WFPC2 and NICMOS observations were obtained for 10 Type Ia supernovae in the redshift range 0.36—0.86. These observations, including final references where necessary, are now complete, and the results are about to be submitted for publication. A preliminary Hubble diagram was presented January 2002 AAS meeting. The cosmological results from these SNe (Knop *et al.*) are in close agreement with results from the first supernova results (Perlmutter *et al.* 1999) that gave direct evidence for a cosmological constant.

[UPDATE THE FOLLOWING] These data are included in Figures 1 and 2 in this proposal. The lightcurves provided by WFPC2 for these supernovae (Figure 3 c& d) were excellent; at the higher redshifts, these lightcurves provide a substantially better measurement of the calibrated supernova magnitude than those for comparable supernovae observed only from the ground. The color information provided by NICMOS (see Figure 4) was only possible from HST. The improvement of the confidence limits on the cosmological parameters Ω_M and Ω_Λ (Figure 2b) are as good as we had previously predicted. Papers presenting the cosmological results from these data will be submitted in 2001.

GO-7336 and **DD-7590**: Perlmutter *et al.*, 1998, Nature, 391, 51 reported the results of our HST and ground-based imaging and Keck spectroscopic observations of SN1997ap, then the *highest redshift* ($z = 0.83$) *spectroscopically confirmed* Type Ia supernova. The HST portion is based on a total of 4 orbits.

Perlmutter *et al.*, ApJ, 1999 reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. HST observations of two $z = 0.83$ are included in the analysis. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.

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NOTES FOR US WHILE WRITING THIS PROPOSAL:

List of Topics for Description of Observations and Coordinated Observations

1. Describe the SNLS (and Essence?) projects well enough to make it clear that sufficiently high-signal-to-noise observations in restframe B and V band will be available throughtout the lightcurves of these SNe that the B_{max}, B-V color, date of max (in B and hence in I), and stretch will all be known to a precision that is better than needed for the known intrinsic dispersion of the methods. Also explain how the supernovae will be triggered well before maximum I band light, and we will be able to predict the date for the NIC F110M observation far enough in advance to schedule the SN.

2. Describe the plan for a couple of SN observation slots per week for 15 weeks (if we are doing two ground-based fields) that will be filled by the appropriate SN as it comes up. Occasionally this slot may become the CMAGIC day 17 slot, if we don't have a new SN at the right time, perhaps?

3. Point out that the final "reference" orbits to image the host galaxy without the SN will not be obtained during this Cycle, but one year later.

4. Make it clear that most (or all) of SNe will likely come from the SNLS set since one of the proposers (Reynald Pain) is a leader of that project, but that the Essence data and discovery announcements are publicly available and we would be happy to follow those SNe as appropriate.

5. Provide a signal-to-noise calculation from the NICMOS ETC showing that we achieve our desired SNR with two supernovae per orbit for the observations at lightcurve maximum, and one SN per orbit at the CMAGIC day 17, even after the final host galaxy images are subtracted off. Note that the host galaxy images cost another half-orbit per SN for 20 SNe and a full orbit per SN for the 10 that are observed with CMAGIC day 17 observations. The total requested orbit count would then be
30 SNe at 1/2 orbit each at max = 15 orbits
(OR drop this to 24 SNe .... = 12 orbit)
10 SNe at 1 orbit at day 17 = 10
20 SNe at 1/2 orbit final ref = 10
(OR drop this to 14 SNe ... = 7 orbits)
10 SNe at 1 orbit final ref = 10
– – – – – – – – – – – – – – – –
Total: 45 orbits
(OR drop this to total 39 orbits)

[State that this is 25 orbits to be scheduled this Cycle + 20 to be scheduled next Cycle.] (OR .... 22 + 17)

6. [[[NOT YET WRITTEN INTO PROPOSAL]]] Show that we have thought about the "persistent cosmic ray" problem for NICMOS, which at worst will cut out 5% of our SNe (based on our previous experience with NIC2) and at best can be cut out by PSF fitting given the better pixel sampling of NIC1.